Linking the Surf Zone and Inner Shelf: Cross-shore Transport Mechanisms

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NPS Award Number: (N0001409WR20221, N0001409WR20222)

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RSMAS Award Number: (N000140710556)

LONG-TERM GOALS

The long-term goals are to understand surf zone processes, in particular cross-shore exchange related to rip current systems through field observations and numerical modeling. Rip currents occur commonly on most beaches and dominate many. It is recognized that beaches with straight and parallel contours are not a stable morphologic configuration, whereas more complex beaches, which support the existence of rip current morphology, are stable and more common.

OBJECTIVES

The research objectives of the proposed work are two-fold. The first is associated with obtaining new observations of the cross-shore exchange between the surf zone and the inner shelf that utilize a suite of *in situ* and Lagrangian measurement systems. The second applies a numerical model (Delft3D) to evaluate the mechanisms responsible for the cross-shore exchange and relate the complex flow dynamics of the rip current system and its interaction with the surface wave field and bottom topography to the observations.

The specific experimental objectives are to observe:

1) the vertical structure of the flow from surf zone to inner shelf at the mean and very low frequency band(VLF, 0.0005-0.004Hz)
2) the propagation of surface drifters deployed in the rip currents just outside of the surf zone under a wide range of environmental conditions
3) the (re-) entering of surface drifters initially present on the inner-shelf into the surf zone

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**
4. TITLE AND SUBTITLE **Linking the Surf Zone and Inner Shelf: Cross-shore Transport Mechanisms**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Postgraduate School,Oceanography Department,Spanagel 327c,Monterey,CA,93943**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S)
		11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

The specific numerical objectives are to evaluate:

4) The vertical flow model description at the wave-group scale from surf zone to inner shelf comparing with the Eulerian in-situ observations

5) The Stokes drift contribution to the modeled Lagrangian surface flow from surfzone to inner shelf using both Eulerian and Lagrangian observations

6) The description of the processes responsible for the cross-shore exchange between surfzone and inner shelf for a wide range of environmental conditions.

APPROACH

We (MacMahan, Reniers, Thornton, Swick, Brown, & Gallagher) conducted a Rip current EXchange experiment, REX, at Sand City, Monterey Bay, CA in May 2009. A combination of *in situ* Eulerian measurements, remote sensing techniques, and Lagrangian measurements were deployed. The Eulerian measurements consisted of an alongshore of self-contained ADCPs were deployed slightly seaward of wave-breaking spanning a rip channel and a CTD deployed within the surf zone. The alongshore array of bottom-mounted ADCPs captures the alongshore variability in vertical flow structure within a rip channel. 40 surfzone drifters with accurate GPS-tracking were deployed for three hours for nine different days under varying wave and tidal conditions to quantify the spatial variation in mean Lagrangian flow, dispersion, and diffusion. The GPSs after post-processing have an absolute position error of < 0.4 *m* and speed errors of < 3 *cm/s* (MacMahan et al., 2009).

Concurrent numerical model predictions of the local hydrodynamic conditions were performed to help in the deployment of the surfzone drifters and the execution of jet-ski surveys. These computations are based on the transformation of deep water directional spectra to the nearshore, including the wave groups to simulate the three dimensional infragravity time scale surfzone circulations.

Jenna Brown (NPS graduate student), Bill Swick (NPS graduate student), Ron Cowen (NPS tech), Jim Lambert (NPS Tech) Jamie MacMahan (NPS) constructed the surfzone drifters. MacMahan, Reniers (RSMAS), Thornton (NPS), Gallagher (Franklin and Marshall), Brown (NPS), and Swick (NPS) were responsible for instrument deployment, maintenance, data archiving, removal, drifter depoyments, and bathymetric surveys. Currently, there is 1 student utilizing the dataset for her PhD.

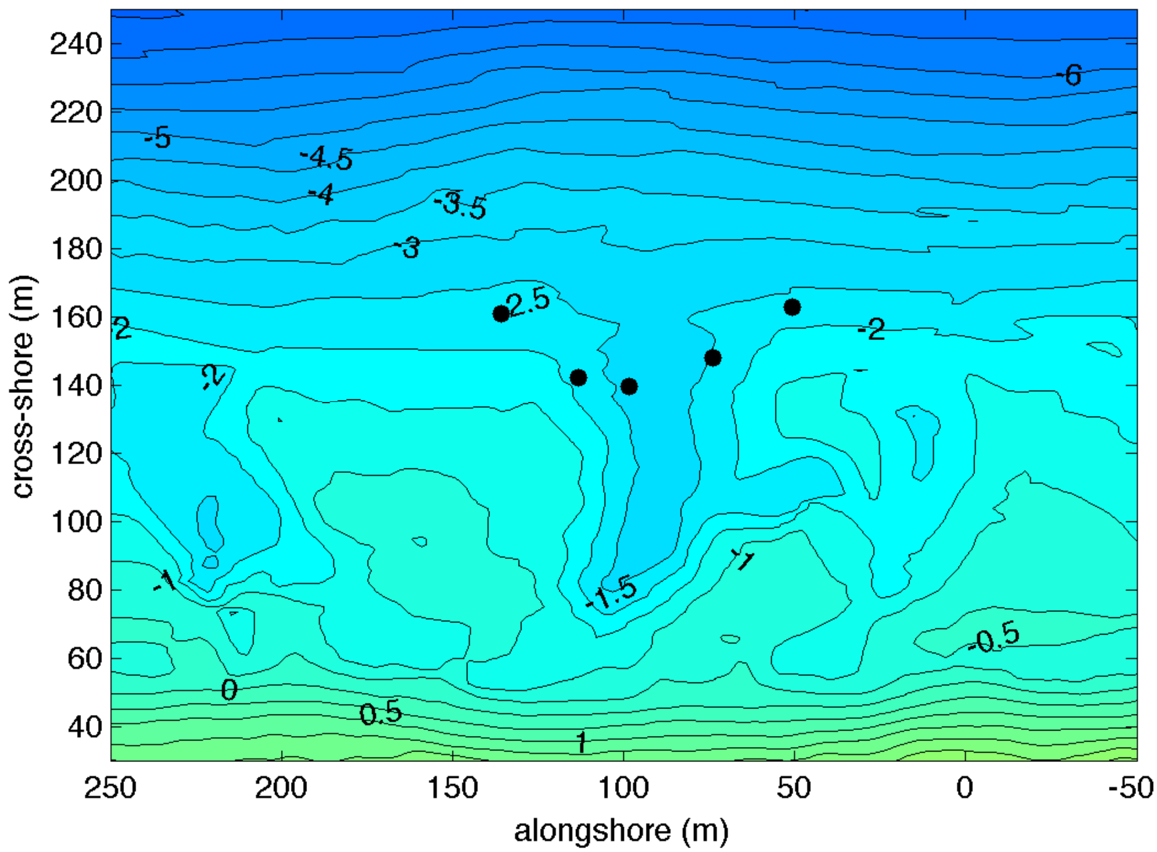

Figure 1. REX Bathymetry. Black dots represent locations of upward-facing self-contained ADCPs.

WORK COMPLETED

We successfully completed the experiment and deployed the ADCPs across the rip channel (Figure 1). We performed 9 drifter deployments under various wave, tidal, and surfzone flow conditions. We performed 5 bathymetric surveys over the course of the experiment. We are still in the midst quality controlling the data.

RESULTS

The results are preliminary and the investigations are ongoing. We deployed 40 drifters within a current near the offshore surfzone boundary. This allowed the drifters to exit the surf zone due to the rip current. The drifter speed tracks show that for the most part that once the drifters exit the surf zone, they did not re-enter the surf zone (Figure 2). Instead they traveled at a relatively constant speed along the shoreline outside of the surf zone. A few drifters did migrate back into the surf zone for the floated around in the surf zone highlighting the rip current circulation pattern before exiting the surf zone again. Some drifters moved farther offshore, which is hypothesized to be associated with rip current pulsations from neighboring rip currents. These results are consistent with previous observations from RCEX, but highlight the complexity associated with cross-shore exchange.

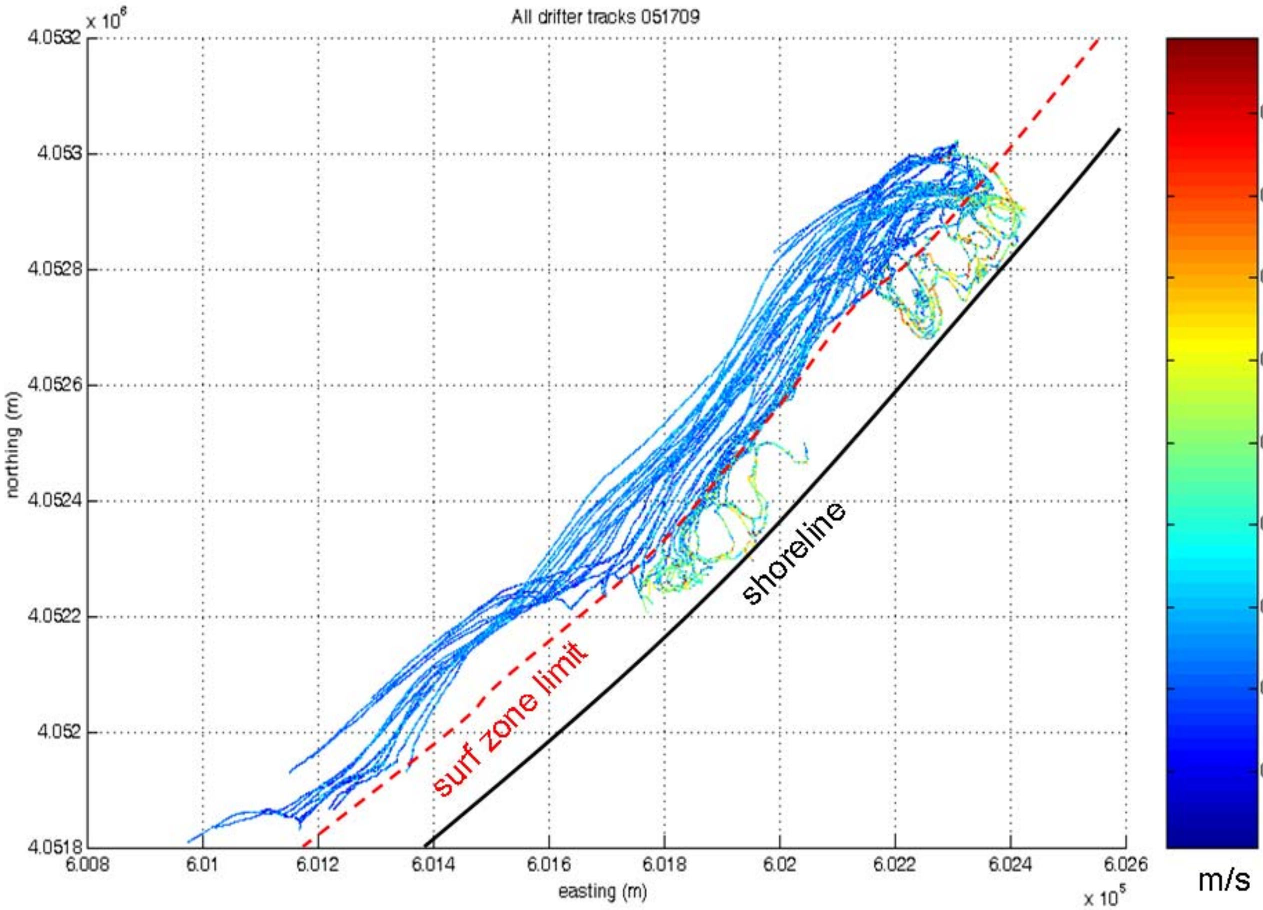

Figure 2. Drifter speed tracks for 40 GPS-equipped drifters deployed at the seaward edge of the surf zone (red-dashed line) in a rip current. Black line represents the position of the shoreline. Speed colorbar plotted to the right.

Preliminary results from the ADCP deployed in the center of the rip channel are discussed. The 3-hr average rip current velocity increases with increasing wave energy and decreasing water depth (Figure 3). There is appears to be minimal vertical variation. We are investigating the VLF rip current pulsations. The velocity data are low-pass filtered with a frequency cut-off of 0.004Hz. Complex correlation analysis determines the average angular displacement and correlation between a pair of complex velocity vectors (Kundu, 1976). Using this analysis, we can determine a weighted average phase angle, degree of correlation, and time lag between vector time series. The 2D VLF horizontal velocity vector is expressed as $w(t)=u(t)+iv(t)$, then the complex correlation coefficient two vector series pairs is defined (Kundu, 1976) as

$$\rho = \frac{\langle w_1^*(t) w_2(t) \rangle}{\langle w_1^*(t) w_1(t) \rangle^{\frac{1}{2}} \langle w_2^*(t) w_2(t) \rangle^{\frac{1}{2}}},$$

where w* is the complex conjugate and brackets are time- average. This normalized inner product indicates a degree of correlation between the velocity pairs. The average angular displacement between series pairs is determined by the corresponding phase angle, α . Average displacement is defined as the counterclockwise angle of the second vector $w_2(t)$ from first vector $w_1(t)$:

$$\alpha = \tan^{-1} \frac{\langle u_1 v_2 - u_2 v_1 \rangle}{\langle u_1 u_2 - v_1 v_2 \rangle}.$$

This average is not an arithmetic mean but a weighted value based upon the instantaneous velocity vector magnitudes. As the analysis from a pair of vector series yield a solution set of length t, the time (τ) of the maximum correlation allows temporal relationships to be observed. Much like an autocorrelation plot, shows any time lead/lag between the series pairs. If maximum correlation occurs at = 0, then no temporal shifts are detected. The vertical complex correlation is high throughout the water column.

The experiment was highly successful in providing many necessary observations for evaluating rip current dynamics.

DELFT3D MODEL CALCULATIONS

The cross-shore exchange of surfzone and inner shelf is examined with Delft3D model calculations. To that end we consider (*Lagrangian coherent structures*) (LCSs), a novel dynamical systems notion (Haller, 2000), which have recently been applied to shelf-scale circulation systems (e.g. Lekien et al., 2005). Here, LCSs are computed based on model predicted surface velocities to study the effects rip current pulses associated with flow motions at the VLF time scale on the transport and fate of floating surfzone material. LCSs wholly control the motion of passively advected tracers in unsteady flows. Consequently, LCSs provide an unambiguous means of identifying rip-current pulses.

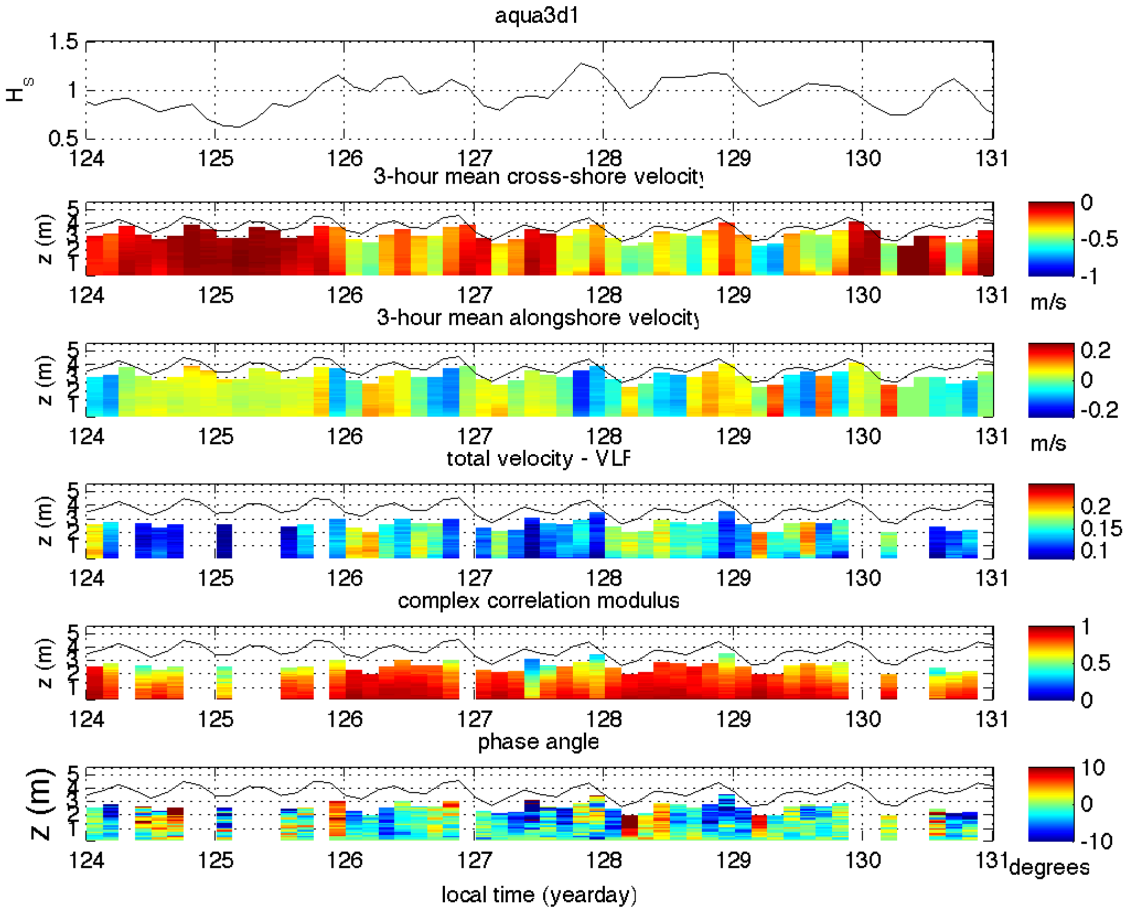

Figure 3. 3-hr results from ADCP located in the center of the array in Figure 1. a) Significant wave height, b) mean cross-shore velocity, c) mean alongshore velocity, d) total VLF energy, e) complex correlation relative to the lowest bin, and f) complex phase angle relative to the lowest bin. Values are contoured through the vertical with corresponding color scales plotted to the right for yeardays 124-131.

The identification of LCSs is obtained with the finite-time Lyapunov exponent (FTLEs). The FTLE gives information on the maximum expansion or contraction rate for pairs of passively advected particles (e.g. representative for the surface drifters). The FTLEs are calculated with the MANGEN software package (Lekien et al., 2005, www.mangen.org). The computed unsteady surface velocity field of the nearshore circulation at a time t0 is seeded with an initially uniformly distributed set of particles (dx = 2 m, dy = 2 m). Next the particle position at -t0 is determined by calculating the advection with a fourth-order Runge-Kutta-Fehlberg algorithm and a third order interpolation for -t0 = 10 minutes. The time integration interval is set to 10 minutes representing the VLF flow dynamics observed in the rip current circulations. Choosing a larger time scale (i.e. > O(hr)) introduces long-term diffusion and dispersion associated with the larger scale nearshore flow circulations thereby obscuring the VLF contribution (Brown et al., 2009). Calculating the FTLEs allows for identifying repelling (> 0) and attracting (< 0) LCSs by maximizing ridges of the FTLE field (e.g. Shadden et al., 2006).

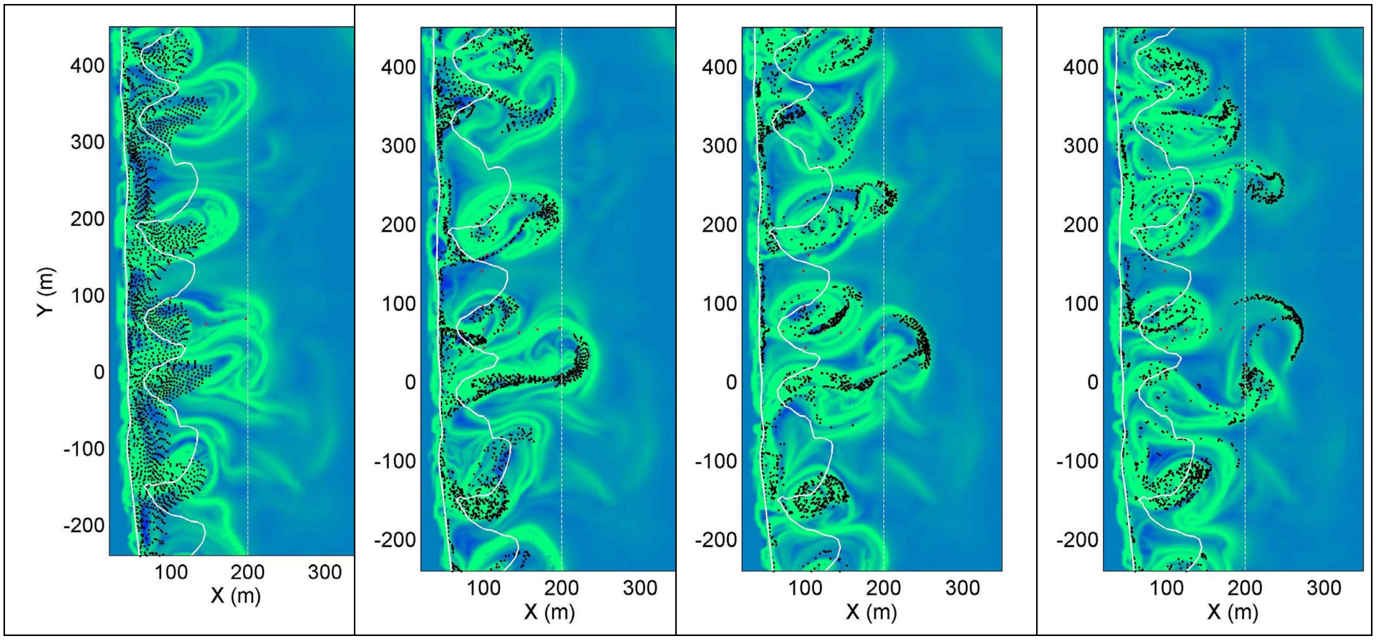

Figure 4. Snapshots of FTLE field in s^{-1} and computed drifter positions 1, 3, 5 and 9 minutes (black dots in panels 1 to 4 from left to right) after virtual drifter seeding for yearday 124 drifter field deployment displaying the time evolution of attracting LCSs associated with VLF dynamics. Initially uniformly distributed drifters quickly converge along the LCS material lines (green ridges corresponding to high FTLE values) forming narrow streaks with occasional exits from the surfzone (indicated by the dashed white line) at locations of high VLF intensity. Bottom contours at 1.5 m depth and shore line (solid white lines) given as a reference.

The computed LCSs in the nearshore display many thin layers of high FTLE-values centered loosely around a core. Each layer represents a transport barrier and as a result surface floating material, represented by the virtual drifters, is trapped between the layers moving in a circular fashion. The space between the adjacent FTLE-ridges is often very narrow, resulting in the collection of surface floating material in thin streaks. This is amply demonstrated in the rapid transition just after the deployment of the virtual drifters (compare panels 1 and 2 in Figure 4), where the initially widely distributed drifters quickly converge along the LCSs. Only in the inner core the drifters can move freely resulting in patch-like distributions (e.g. around Y = -150 m). At locations of rip currents the LCSs are elongated in the cross-shore allowing the transport of drifters offshore. Once the drifters reach the offshore extent of the LCS they can only move in the alongshore direction, thereby generally re-entering the surfzone. Only occasionally the outer LCS filaments peel off and become detached from the inner layers. If this happens at the outer surfzone, material trapped by the detaching filament(s) is transported offshore outside of the surfzone (around Y = 0 m and Y = 250 m in Figure 4) with the drifters slowly converging on the transport barrier forming a thin line (panel 4 in Figure 4). This transport barrier corresponds to the outer edge of the unsteady diverging rip flow corresponding at the time scale of the VLF-motions.

The effect of VLFs on the ejection of surfzone floating material on a rip channeled beach has been assessed by calculating LCSs within the nearshore surface velocity field obtained with a verified three dimensional wave and flow model resolving the wave group dynamics. The LCSs explain the occasional exit of surface drifters from the surfzone due to VLF motions as the outer FTLE-filaments detach from the nearshore rip circulation.

In addition, the frequently observed narrow streaks of remnant surface floating material outside of the surfzone on rip channeled beaches is explained by the closely spaced thin material transport barriers identified as ridges in the FTLE field. In contrast, the distribution of surface floating material within the surfzone can be quite patchy where drifters collect at the cores of the LCSs.

RELATED PROJECTS

Sea Breeze Exchange

Cross-shore exchange by strong (cross-shore wind stress, $\tau_{sx} > 0.05$ Pa) diurnal (7-25 hrs) sea breeze events are investigated using two years of continuous wind, wave, and ocean velocity profiles in 13 m water depth on the inner-shelf in Marina, Monterey bay, California (Hendrickson and MacMahan, 2009). The diurnal surface wind stress, waves, and currents have spectral peaks at 1, 2, and 3 cpd and the diurnal variability represents about 50% of the total variability. During sea breeze relaxation ($-0.05 < \tau_{sx} < 0.05$ Pa), a background wave-driven inner-shelf Eulerian undertow profile exists, which is equal and opposite to the Lagrangian Stokes drift profile, resulting in a net zero Lagrangian transport at depth. In the presence of a sea breeze ($\tau_{sx} > 0.05$ Pa), a uniform offshore profile develops that is different from the background undertow profile allowing cross-shore Lagrangian transport to develop, while including Lagrangian Stokes drift. The diurnal cross-shore current response is similar to subtidal (> 25 hrs) cross-shore current response, as found by Fewings et al. (2008). The seasonality of waves and winds modify the diurnal sea breeze impact. It is suggested that material is not transported cross-shore except during sea breeze events, owing to near zero transport during relaxation periods. During sea breeze events, cross-shore exchange of material appears to occur onshore near the surface and offshore near the sea bed. Since sea breeze events last for a few hours, the long-term cross-shore transport is incremental each day.

IMPACT/APPLICATIONS

These new observations are important for calculating the transport of surface drifters but also sediment fines, algae, bubbles and other organic matter and as a result will also impact the predictions of both water clarity and water qualitity. The observations will be further evaluated with Delft3D.

REFEERENCES

Brown, J.W., J. MacMahan, A. Reniers, and E. Thornton, 2009, Diffusivity on a Rip Channeled Beach, accepted to *J. Geophys. Res.*

Fewings, M., S.J. Lentz, and J. Fredericks. 2008. Observations of Cross-Shelf Flow Driven by Cross-Shelf Winds on the Inner Continental Shelf. *Journal of Physical Oceanography* 38, no.11, 2358–2378.

Haller, G., 2000, Finding finite-time invariant manifolds in two-dimensional velocity fields, *Chaos, 10*, 99-108.

Kundu, P. K. 1976. Ekman Veering Observed near the Ocean Bottom. *Journal of Physical Oceanography*, 6, 238-242.

Lekien, F., C. Coulliette, A.J. Mariano, E.H. Ryan, L.K. Shay, G. Haller and J.E. Marsden, 2005, Pollution release tied to invariant manifolds: A case study for the coast of Florida, *Physica D, 210*, 1-20.

MacMahan, J., J. Brown, and E.B. Thornton, 2009. Low-cost handheld Global Positioning Systems for measuring surf zone currents, *J. Coastal Res*, DOI: 10.2112/08-1000.1.

Shadden, S.C., F. Lekien and J.E. Marsden, 2006, Definition and properties of Lagrangian coherent structures from finite -time Lyapunov exponents in two-dimensional aperiodic flows, *Physica D, 212*, 271-304.

RELATED PUBLICATIONS

MacMahan, J., J. Brown, and E.B. Thornton, Low-cost handheld Global Positioning Systems for measuring surf zone currents, *J. Coastal Res*, DOI: 10.2112/08-1000.1, 2009

MacMahan, J. H., Thornton, Ed. B., Reniers, Ad. J.H.M., Stanton, Tim P., Symonds, Graham, Rip Currents Associated with Small Bathymetric Variations, *Marine Geology*, doi: 10.1016/j.margeo. 2008.08.006, 2009.

MacMahan, J. H., J. Brown, A. Reniers, J. Brown, E. B. Thornton, A. J. H. M. Reniers, T. P. Stanton, Henriquez, M., E. Gallagher, J. Morrison, M. Austin, T. Scott; N. Senechal. Mean Lagrangian Flow Behavior on an Open Coast Rip-channeled Beach, *accepted upon minor revisions to Mar. Geol., 2009.*

Reniers, A., J.H. MacMahan, E. B. Thornton, T. P. Stanton, Henriquez, M., J. Brown, J. Brown, and E. Gallagher, Surfzone Retention on a Rip Channeled Beach, *in press* J. *Geophys. Res., 2009.*

Brown, J.W., J. MacMahan, A. Reniers, and E. Thornton, Surfzone Diffusivity on a Rip Channeled Beach, accepted to J. Geophys. Res, 2009.

Hendrickson, J. and J. MacMahan, 2009, Diurnal Sea Breeze Effects on Inner-shelf Cross-Shore Exchange, *Continental Shelf Research*, doi:10.1016/j.csr.2009.08.011

Austin, M.J., T. M. Scott, J.W. Brown, J.A. Brown, J. MacMahan, Macrotidal rip current experiment: circulation and dynamics, *J. Coastal Res. SI 56, 2009.*

RELATED PRESENTATIONS

Geiman, J. J. Kirby, A. Reniers, J. MacMahan, J. Brown, J. Brown, and T. Stanton, Wave-Averaged and wave-resolving simulations of the RCEX experiment: Mean flows and Drifter Dispersion, AGU Fall Meeting, 2008

Reniers, A. J. MacMahan, Surf zone Exchange on a Rip Channeled Beach, AGU Fall Meeting, 2008

Hendrickson, J. J. MacMahan, E. Thornton, M.Cook, T. Stanton, A. Reniers. Diurnal Cross-Shore Exchange on the Inner-Shelf in Southern Monterey Bay, CA, AGU Fall Meeting, 2008

Brown, J., J. MacMahan, A. Reniers, J. Brown, E. Thornton, T. Stanton, M. Orzech, Alongshore Sinuous Currents on a Rip-Channeled Beach, AGU Fall Meeting, 2008

Thornton, E., J. MacMahan, A. Reniers, J. Brown, T. Stanton, J. Brown, Rip Current Retention, AGU Fall Meeting, 2008

O' Neill, J. MacMahan, A. Reniers, E. Thornton, T. Stanton, J. Brown, Vertical Behavior of Rip Current Pulsations Outside the Surf Zone, AGU Fall Meeting, 2008

MacMahan, J., E. Thornton, T. Stanton, A. Reniers, J. Brown & J. Brown, Eulerian and Lagrangian measurements of rip currents during RCEX, ICCE 2008

Reniers A., J. MacMahan, E. Thornton, and T. Stanton, Modeling of 3D structure of rip current flows at RCEX, ICCE 2008

Kirby J.T., J. H. MacMahan, A. Reniers, J.Geiman, J. Brown, and T. Stanton, Model/Data Comparison for Lagrangian Trajectories and Mixing Estimates over Complex Nearshore Bathymetry, EuroTechnical Conference 2008.